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Numerical and Flight Simulator Test of the Flight Deterioration Concept

John McCarthy and Vern Norviel

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1.0 INTRODUCTION

In several recent reports, McCarthy et al. (1979, 1981) and Frost et al. (1978a, 1978b) have described in detail a prototype system that utilizes an airport Doppler radar and a numerical aircraft performance model to detect and warn of low-level wind shear. Figure 1 illustrates the concept in stages, leading to the production of an approach deterioration parameter (ADP). This parameter provides a quantitative evaluation of how an aircraft will perform on approach. In this report the ADP will be modified to "Flight Deterioration Parameter," or FDP, to signify its applicability to approach, departure, or near level terminal transition flight.

In McCarthy et al. (1981), it was clearly established that radial winds along airport approach and departure paths could be measured by a pulsed microwave Doppler radar. In those studies, a simple fixed-stick numerical aircraft response model (see McCarthy et al., 1979) was used to measure FDP. It was shown that for the more intense low-level wind shear cases (although never greater than moderate shear), the simple model could adequately evaluate actual aircraft performance. The principal shortcoming of the fixed-stick model is, of course, no pilot controls (i.e., elevator and thrust) are present. Consequently, a wind shear encounter which could be well accounted for by a pilot is not considered.

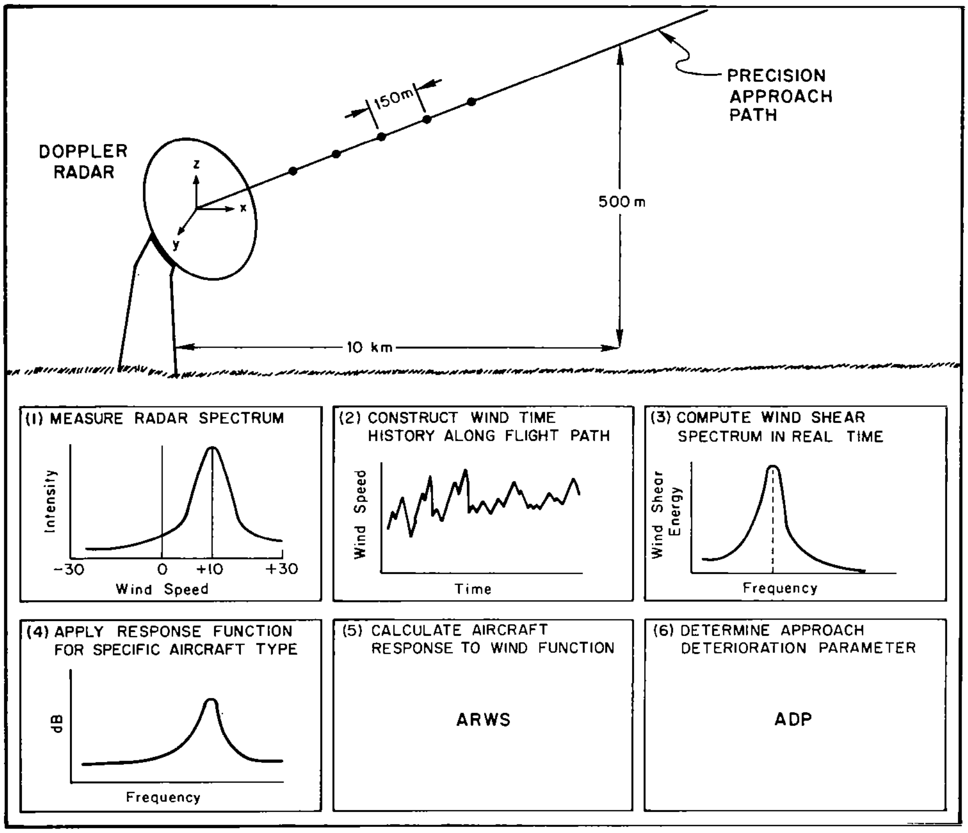

Figure 1. Diagrammatic illustration of wind shear detection and warning system. Process is sequential, starting from Doppler radar measurement of winds along the precision approach path, and ending with a prediction of approach deterioration for a particular class of airplane. In a real-time system, steps 1-6 would take place within several seconds by use of a computer slaved to the Doppler.

In Turkel and Frost (1980), a pilot-aircraft modelling response to a wind shear system is described. In this numerical model, a simulated pilot response is included, whereby elevator and thrust changes are incorporated into the response system. As in the McCarthy et al. (1981) work, the Turkel and Frost model allows for the calculation of FDP values.

A significant uncertainty remained regarding a real world calibration of these parameters. For example, is a pilot-aircraft FDP a realistic parameter for a real piloted aircraft encounter with a low-level wind shear situation? To best resolve this uncertainty, actual piloted flight of an aircraft into dangerous low-level wind shear would be necessary, a less than popular and wise venture. The obvious alternative would be use of a manned flight simulator to test, or calibrate, FDP values for a variety of wind shear cases. In this test, it would be assumed that a flight simulator accurately depicts real aircraft flight into wind shear, as well as a true representation of pilot response.

This report describes the results of several types of FDP calibration attempts. In August, 1980, FWG and MCS conducted a number of FDP test flights on a Boeing-727 manned flight simulator at the NASA Ames Flight Research Center, Mountain View, California. Results of these tests will be reported separately by FWG. In October, 1980, a similar series of tests were conducted at the United Airlines Flight Training Center, Denver, Colorado. The simulator tests that are reported herein concern only those conducted at United Airlines (UAL).

After the UAL tests were run and evaluated, it became obvious that those test results required comparison to the Turkel and Frost model. Section 3.0 reports on several types of comparisons. In the last section, a general discussion precedes the conclusion.

2.0 THE TESTS AT UNITED AIRLINES

A series of manned flight simulations were conducted on a Boeing-727 simulator at the UAL Flight Training Center in Denver on 7 October 1980. All approaches were flown by UAL simulator test pilot Fred Watts.

Twelve B-727 ILS approaches flown by Watts, considered a theoretical microburst single full sine wave wind shear input, encountered headwind first at 426 m (1400 ft) AGL. The simulator phugoid frequency was determined to be 0.025 Hz, or at a period of 40 s. Wave amplitudes of 5, 10, 15, 20, 25, and 30 m/s were flown. Eight of the 12 approaches were flown at the 40 s period, while the remaining were at 10, 20, 80, and 160 s each.

Six flight deterioration parameters were used, as outlined in Table 1. FDP definitions 1 and 3 represent the $\Delta h'$ and $\Delta u'$ parameters defined by McCarthy et al. (1979). The remainder were identified by Turkel et al. (1981). Note that FDP definitions 1, 2a, and 2b are height-based parameters, while 3, 4a, and 4b are velocity perturbation parameters. Height FDP estimations refer to height departures of the aircraft from the glide slope, while velocity FDP's are airspeed departures from the nominal approach speed. (For the UAL flights, the nominal airspeed was 124 kts.). Table 2 gives the FDP values for the 40 s phugoid frequency wave. Figure 2 shows a plot of the FDP

TABLE 1. Flight Deterioration Parameters Used in UAL Simulation Evaluation

1.	$\sqrt{\frac{1}{T_L}\int_0^{T_L} (HP - HG)^2 dt}$	where T_L is total landing time, HP is aircraft altitude, HG is glide slope height.
2a.	$\frac{1}{T_n}\int_0^{T_n} \frac{HP}{HG}\, dt$	where HP/HG above or on glide slope ≥ 1.0 and T_n is time above or on glide slope. T_n/T_L is percentage of time above or on glide slope.
2b.	$\frac{1}{T_m}\int_0^{T_m} \frac{HP}{HG}\, dt$	where HP/HG below glide slope < 1.0 and T_m is time below glide slope. T_m/T_L is percentage of time below glide slope.
3.	$\sqrt{\frac{1}{T_L}\int_0^{T_L} (V_a - V_{a_o})^2 dt}$	where V_a = airspeed, V_{a_o} = reference airspeed.
4a.	$\frac{1}{T_i}\int_0^{T_i} (V_a - V_{a_o}) dt$	for $V_a - V_{a_o} \geq 0$ where T_i is time airspeed is equal to or greater than reference airspeed. T_i/T_L is percentage of time above or equal to reference airspeed.
4b.	$\frac{1}{T_k}\int_0^{T_k} (V_a - V_{a_o}) dt$	for $V_a - V_{a_o} < 0$ where T_k is time airspeed is below reference airspeed. T_k/T_L is percentage of time below reference airspeed.

TABLE 2. United Airlines Flight Deterioration Parameter Data for 40 s Period Sine Wave, Head-wind First, Piloted by Watts.

Wave Amplitude (m/s)	Flight Deterioration Parameter 1($\Delta h'$) (m)	2a --	2b --	3($\Delta u'$) (m/s)	4a (m/s)	4b (m/s)
6.1	12.8	1.008	0.946	1.55	1.449	-0.607
12.2	22.2	1.022	0.874	2.85	2.187	-1.263
12.2	16.7	1.047	0.935	2.34	2.371	-1.039
18.3	30.5	1.043	0.877	3.52	3.268	-1.364
18.3	26.8	1.048	0.858	3.04	4.145	-0.767
24.4	34.0	1.069	0.799	4.80	5.419	-1.555
30.5	92.6	1.072	0.487	5.46	6.698	-1.946

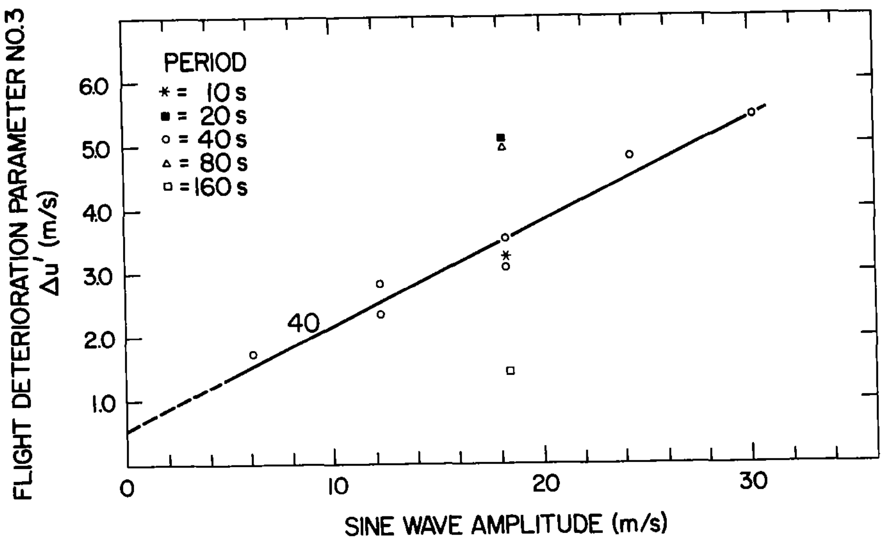

Figure 2. Flight deterioration parameter no. 3 (Δu') plotted against sine wave amplitude for UAL case. Linear regression represents 40 s phugoid cases.

number 3 ($\Delta u'$) as a function of sine wave amplitude. A linear regression for the 40 s period case is shown, while points at 18.3 m/s for the other frequencies are plotted. It was regrettable that sufficient data points at the other frequencies were not collected. Figures 3 and 4 present similar information for FDP Numbers 4a and 4b.

Through these analyses, the correlations for the height flight deterioration parameters were poor. Consequently, they are not plotted. A general appreciation for the improved correlation for velocity perturbation over that of height departure is shown in Figure 5 (after McCarthy et al., 1979). Furthermore, the evolution of this work has suggested that airspeed fluctuations seem to be more critical to pilot monitoring of aircraft performance.

In examining Figures 2-4, all plots are really quite linear with the regressions passing remarkably close to the appropriate origins. Unfortunately, only a single point was collected for periods other than the phugoid. When the other period points are examined, no clear picture emerges regarding the frequency dependency of the parameters. This dependency is graphically illustrated in Figure 5.

It was expected that the same frequency dependency concept of McCarthy et al. (1979) and Turkel and Frost (1980), which indicates a maximum flight deterioration at the phugoid frequency, is not operative in the UAL training-

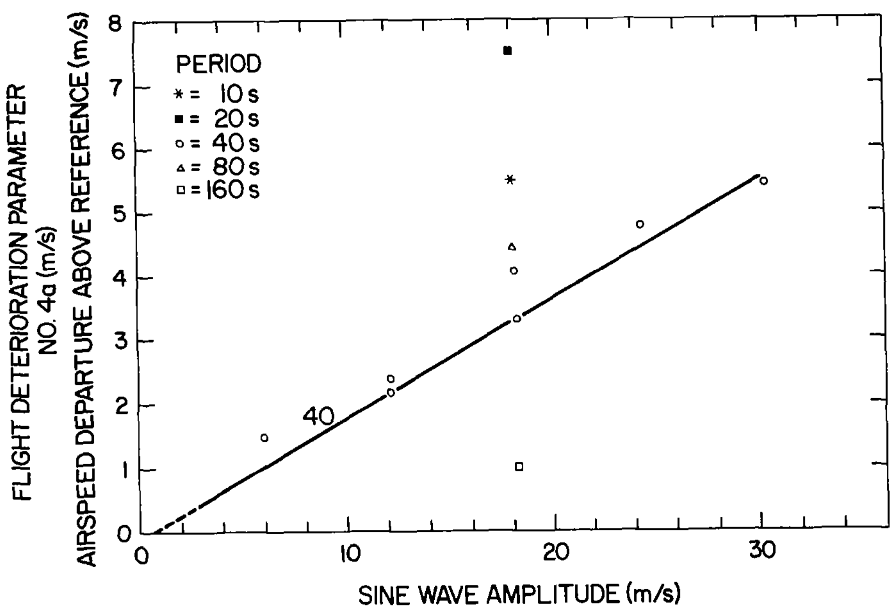

Figure 3. Flight deterioration parameter no. 4a (airspeed departure above reference) plotted against sine wave amplitude for UAL case.

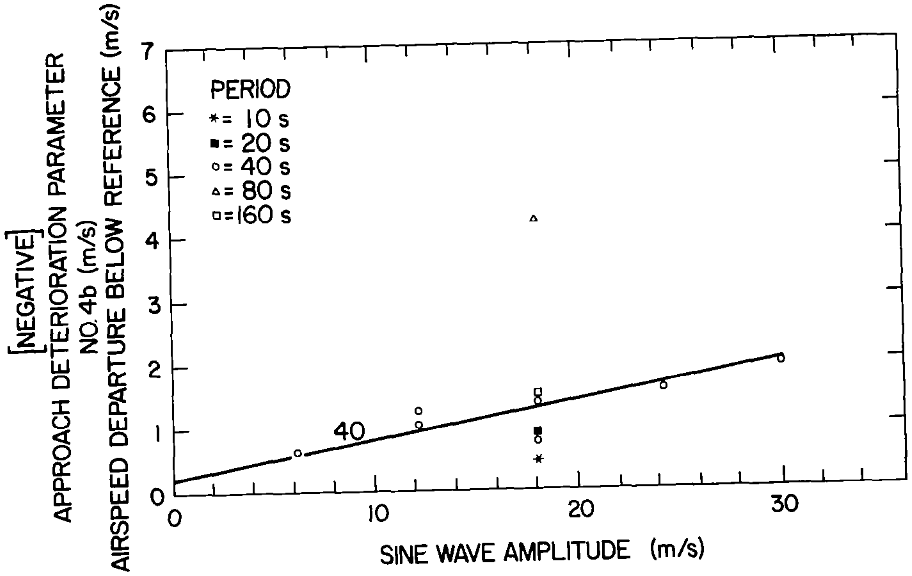

Figure 4. Flight deterioration parameter no. 4b (airspeed departure below reference) plotted against sine wave amplitude for UAL case.

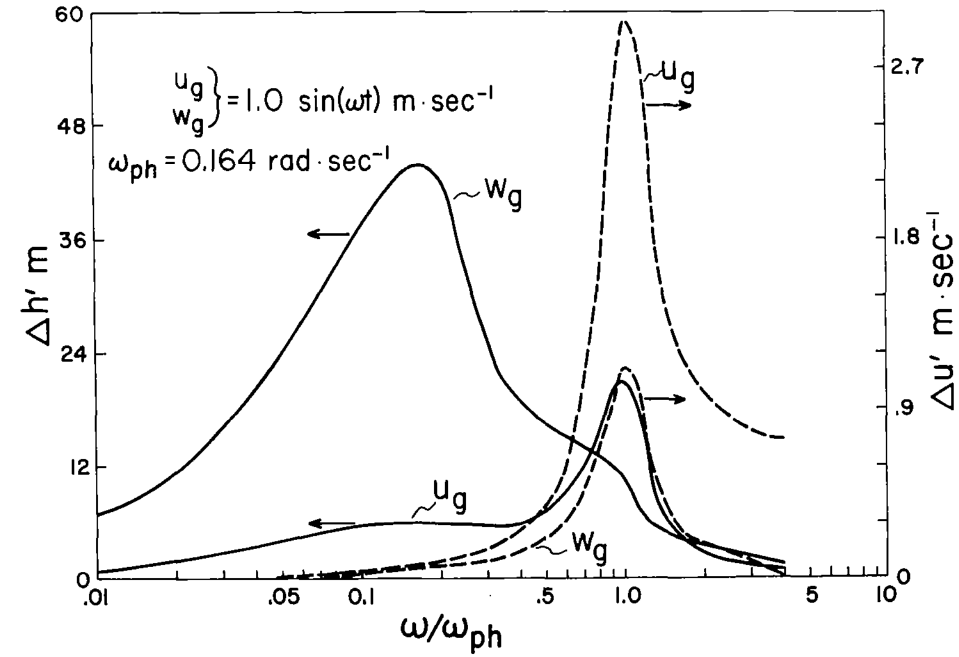

Figure 5. RMS altitude and velocity deviations of a Boeing-727 class airplane to a continuous 1 m/s horizontal (or vertical) sine wave (after McCarthy et al., 1979).

type simulator. A tentative conclusion is that this type of simulator overdamps the phugoid oscillation, thereby destroying the predicted frequency dependency.[1]

Unfortunately, it has not been possible to continue the UAL simulations within the time table of this research. However, simulations with UAL conducted through the National Center for Atmospheric Research at a later date may cast additional light on the problem.

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[1]Discussions with UAL at the recent Fifth Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, Tullahoma, Tennessee, April 1981, confirmed this notion of overdamping.

3.0 TURKEL AND FROST MODEL COMPARISONS

The failure of the UAL simulations to verify model predictions of maximum flight deterioration at the aircraft's phugoid frequency suggested another look at the pertinent aspects of the Turkel and Frost (1980) model. Two general cases were run: pilot response and fixed-stick cases. All input parameters, including wind shear, altitude of encounter, aircraft configuration, etc., were the same as for the UAL simulation; Tables 3 through 8 give FDP values for all model runs. As in the UAL manned flight simulator cases, only the airspeed perturbation cases seemed to have significant correlations, so only those FDP plots are presented in Figures 6-8.

Each plot gives numerical piloted cases for five periods, including the phugoid, and a least-squares linear regression fit for each period. For reference, the UAL phugoid (40 s) period regression and the phugoid fixed-stick regression are indicated. All points that represent crash occurrences are plotted, but are not included in the respective linear regression.

When Tables 3-8 and Figures 6-8 are examined carefully, a number of interesting observations can be made. The deterioration peak at or near the aircraft phugoid period (40 s), or frequency (0.025 Hz), previously understood is verified. A slight variance is seen in FDP

TABLE 3. Model Flight Deterioration Parameter No. 1 ($\Delta h'$), as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed.

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10	(3.28)	8.11 (6.66)	9.36 (13.73)	11.37	12.31	16.53
20	(11.65)	12.04 (24.00)	18.24 (50.53)	21.06	53.29	105.76
40*	(24.81)	25.75 (49.91)	39.75 (99.97)	34.61	79.48	79.39
80	(14.54)	21.82 (29.49)	35.78 (60.08)	39.03	40.34	41.47
160	(12.46)	7.04 (23.91)	9.56 (44.71)	11.38	13.74	19.54

*Phugoid Period

TABLE 4. Model Flight Deterioration Parameter No. 2a, as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed.

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10	(1.05)	1.04 (1.09)	1.06 (1.13)	1.07	1.08	1.10
20	(1.05)	1.10 (1.09)	1.15 (1.15)	1.17	1.22	$\underline{1.04}$
40*	(1.12)	1.21 (1.20)	1.25 (1.23)	1.28	$\underline{1.05}$	$\underline{1.06}$
80	(1.04)	1.14 (1.09)	1.35 (1.18)	1.88	1.62	2.05
160	(1.04)	1.05 (1.07)	1.09 (1.14)	1.13	1.22	1.15

*Phugoid Period

TABLE 5. Model Flight Deterioration Parameter No. 2b, as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed.

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10	(0.97)	0.96 (0.99)	0.97 (0.87)	0.97	0.97	0.96
20	(0.85)	0.99 (0.81)	0.97 (0.72)	0.95	0.79	0.58
40*	(0.83)	0.99 (0.67)	0.94 (0.56)	0.87	0.66	0.64
80	(0.89)	0.94 (0.81)	0.98 (0.67)	0.95	0.94	0.92
160	(0.77)	1.00 (0.67)	0.99 (0.58)	0.99	0.99	0.98

*Phugoid Period

TABLE 6. Model Flight Deterioration Parameter No. 3 ($\Delta u'$) as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed.

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10	(0.74)	1.55 (1.48)	2.65 (3.00)	3.79	4.87	5.99
20	(1.86)	2.78 (3.85)	4.86 (8.00)	6.25	8.39	<u>17.84</u>
40*	(3.44)	5.34 (6.88)	7.98 (13.23)	9.07	<u>12.37</u>	<u>14.05</u>
80	(0.85)	4.67 (1.70)	7.58 (3.57)	10.00	11.91	13.36
160	(0.33)	1.41 (0.67)	2.54 (1.36)	3.67	4.04	4.53

*Phugoid Period

TABLE 7. Model Flight Deterioration Parameter No. 4a, as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed,

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10		1.14	1.75	2.39	2.99	3.19
	(0.52)	(1.03)	(2.01)			
20		2.37	3.88	4.35	6.88	13.68
	(1.55)	(3.18)	(6.66)			
40*		4.86	6.94	8.20	8.61	10.37
	(2.80)	(5.94)	(10.51)			
80		4.20	7.07	9.02	11.58	13.28
	(0.66)	(1.18)	(2.37)			
160		1.16	2.19	3.30	3.56	4.27
	(0.26)	(0.53)	(1.06)			

*Phugoid Period

TABLE 8. Model Flight Deterioration Parameter No. 4b, as a Function of Period and Wave Amplitude, for Piloted Case and (Fixed-Stick Case), Underscore Indicates Airplane Crashed.

Period(s)	Wave Amplitude (m/s)					
	2.5	5.0	10	15	20	25
10	(-0.53)	-1.18 (-1.09)	-1.80 (-2.29)	-2.38	-2.75	-3.53
20	(-1.72)	-2.31 (-3.56)	-3.94 (-7.22)	-5.29	-6.44	-17.73
40*	(-3.07)	-4.09 (-5.75)	-5.94 (-11.58)	-6.69	-12.51	-14.18
80	(-0.73)	-3.76 (-1.85)	-4.49 (-4.20)	-6.31	-7.10	-8.20
160	(-0.30)	-1.28 (-0.62)	-2.29 (-1.29)	-3.19	-3.56	-3.61

*Phugoid Period

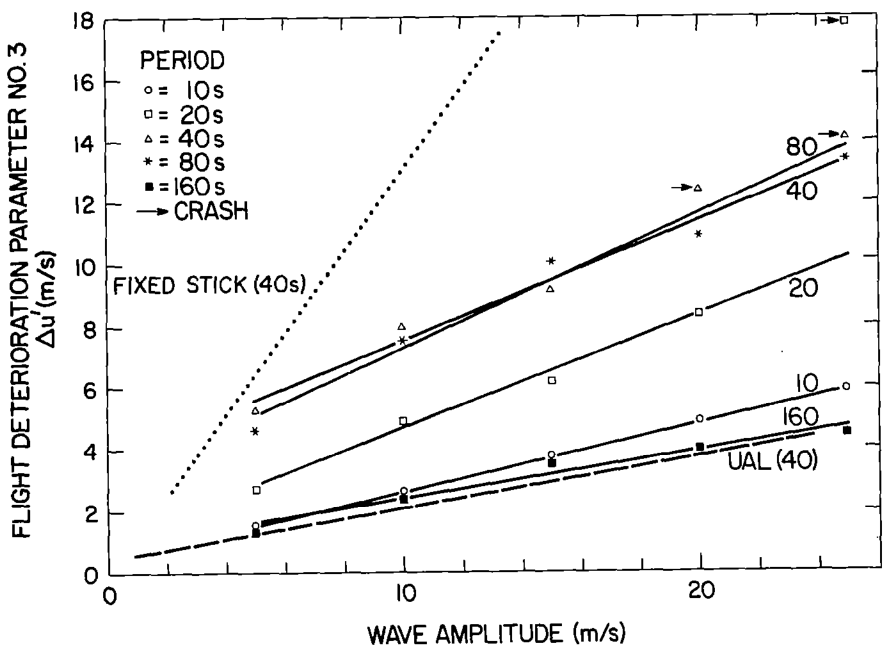

Figure 6. Flight deterioration parameter no. 3 (Δu') plotted against sine wave amplitude for model case. Linear regressions are included for each case, with crash points plotted but not included. For reference, the phugoid period (40 s) regressions for fixed-stick and UAL cases are included.

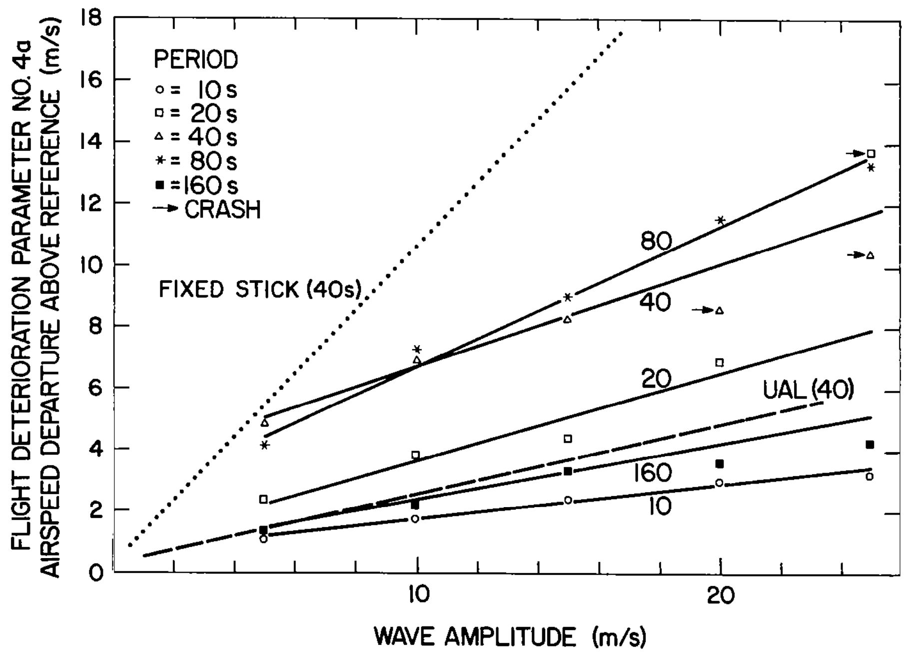

Figure 7. Flight deterioration parameter no. 4a plotted against sine wave amplitude for model case.

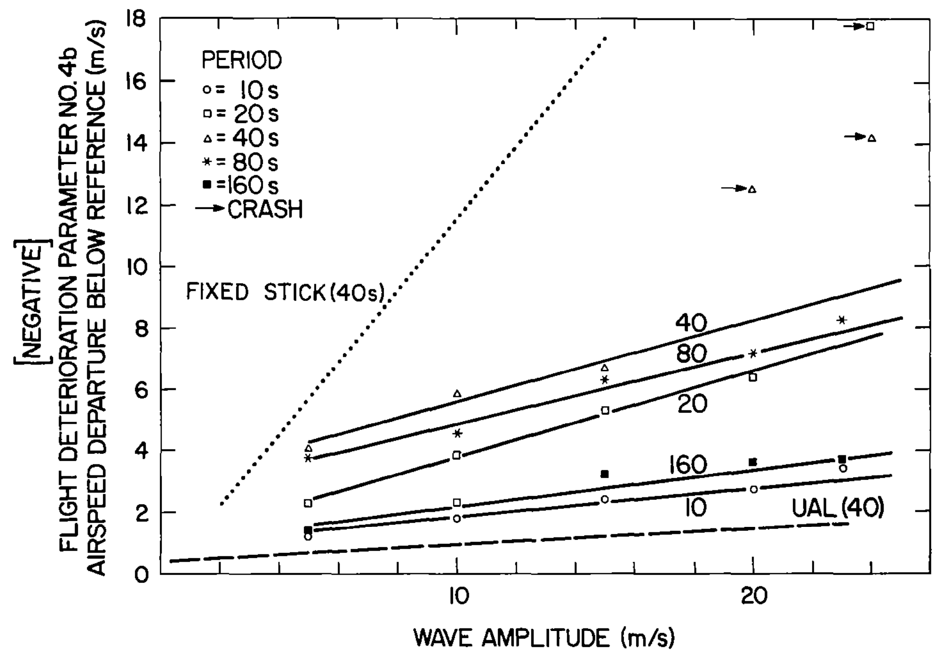

Figure 8. Flight deterioration parameter no. 4b plotted against sine wave amplitude for model case.

numbers 3 and 4a, when the 80s period case is more deteriorated at higher sine wave amplitude. No explanation for this variance is clear, except for some nonspecific aspect of the numerical pilot function.

A second observation is made when the human piloted UAL phugoid regression is compared with the Turkel and Frost model regression at the same period. Clearly, the total human flight deterioration is greatly reduced from the model case. In other words, the model pilot function does not perform nearly as well as a real pilot in a flight simulator. Fundamental questions regarding this observation are left for the last section.

As expected, the fixed-stick FDP values are much higher than either numerical or real pilot cases. This indicates that the extreme deterioration at the airplane's phugoid frequency is greatly reduced by a pilot. Examination of Tables 3-8 for non-pilot fixed-stick cases at the non-phugoid periods (they were not plotted) supports the earlier conclusion of McCarthy et al. (1979) that the deterioration dependence on a narrow frequency zone near the phugoid is most critical.

Finally, the three airspeed related flight deterioration parameters are of similar quality as sensitive predictor variables of wind shear along the flight path. FDP variables 3 and 4a are essentially equal while 4b is somewhat less sensitive. This minor deficiency is a little disappointing since 4b reflects airspeed departure below nominal or, in other words, less flying speed in the direction of aircraft stall.

It is useful to attempt to use the flight deterioration parameterization in a useful example. Please refer to Figure 6 in this example. (For the sake of overall clarity and to maintain continuity to research reported previously in McCarthy et al. (1979, 1981), the FDP number 3, or $\Delta u'$, will be used.) Consider a Boeing-727 flying a nominal (reference) approach airspeed of 67 m/s (130 kts), with an assumed stall speed of 51 m/s (100 kts). Further assume that the FDP is used as a warning flag of serious wind shear. Assume further that if an aircraft has an airspeed reduction to within 5 m/s (10 kts) of stall, it would be in a sufficiently dangerous situation to warrant immediate avoidance of the approach or departure. Consequently, a 10 m/s (20 kt) reduction in airspeed (from 67 m/s (130 kts)) is examined. Since $\Delta u'$ is a root-mean-square determination, an actual 10 m/s (20 kt) reduction is given by

$$\begin{aligned} \text{critical } \Delta u' &= 0.707 \times 20 \text{ kts} \\ &= 14.14 \text{ kts} \\ &= 7.28 \text{ m/s} \end{aligned}$$

Considering Figure 6, and examining the various regression intercepts for 7.28 m/s $\Delta u'$ values, the following sine wave wind shear amplitudes result:

Period	Amplitude (m/s,kts)	Case
40 s	6.0, 11.7	Fixed-Stick
40 s	9.5, 18.5	Model Pilot
40 s	39.6, 76.9 estimated	UAL Pilot

This says that to reach a critical airspeed loss, the phugoid period shear wave amplitude must be 6, 10, 40 m/s (11.7, 18.5, or 76.9 kts), depending on which case is considered.

A somewhat different way of looking at flight deterioration considers a real atmospheric microburst case reported by Fujita et al. (1980). Fujita's analysis of the 29 May 1977 microburst case showed a wind shear amplitude of 31 m/s (60.2 kts). When this amplitude is examined on Figure 6, the following FDP values are estimated (beyond the graph axis):

Period	Amplitude (m/s,kts)	$\Delta u'$ (m/s)	Case
40 s	31, 60.2	40.6	Fixed-Stick
40 s	31, 60.2	15.2	Model Pilot
40 s	31, 60.2	5.6	UAL Pilot

These figures indicate that the documented microburst case would produce large values of $\Delta u'$, and depending on which case is used, dangerous thresholds of $\Delta u'$ could be assumed. In fact, except for the UAL simulator case, the $\Delta u'$ threshold of 7.28 m/s would clearly be adequate for the Fujita situation.

4.0 DISCUSSION AND CONCLUSIONS

The two illustrations at the end of the last section serve to illustrate what may appear to be a failure in a primary objective of this research: the human pilot calibration of previously reported numerical pilot aircraft response models. In fact, a wide variation in flight deterioration parameters is seen for a given wind shear amplitude. In the convolution of this view, a given (and radar-calculated) deterioration parameter may indicate a wide variation in wind shear amplitude. However, these uncertainties reflect the fundamental variability in predicting pilot flying response to a given atmospheric wind input. The UAL pilot, in his simulator, performed better than the numerical pilot, and both outperformed the fixed-stick case. This really is not surprising considering the obvious simplicity of the numerical pilot function reported in Turkel and Frost. Furthermore, how "real" is the manned flight simulator? After all, there is an indication that the phugoid response is overdamped. Likely there are numerous other "simplifications" in this training machine.

The investigators are left with the belief that a <u>precise</u> calibration of the concept is really not necessary. After all, the purpose of the Doppler radar/numerical model low-level wind shear detection and warning system is to identify potential wind shear in the vicinity of an airport, with sufficient quantitation to prohibit approaches and departures. The objective is not to make a precise prediction as to whether an aircraft can penetrate the shear without a disastrous crash; the number of variables are just too many to make that possible.

By again examining Figures 6-8 and the two examples of the last section, the authors can conclude that a "reasonable" calibration of the numerical pilot function model has been performed, as long as the warning concept utilizes conservative criteria. The Turkel and Frost (1980) model serves the threshold warning criteria quite successfully. Perhaps the UAL pilot may be able to successfully penetrate many cases tested here. However, any successful detection and warning system must overwarn to some degree, not to the extent implied by the fixed-stick model, but most appropriately to the extent of the pilot-in-the-loop numerical model. The criteria of $\Delta u'$ of approximately 7.3 m/s or 14.1 kts may be sufficient but conservatively accurate to be suitable as a threshold.

The principal finding of this research recommends that the Turkel and Frost pilot model be implemented as part of the Doppler radar system, using a $\Delta u'$ warning threshold of approximately 14.1 kts. This actually represents an airspeed fluctuation of 20 kts. However, further empirical testing of this threshold is indicated, since the selection of this criteria was based on a manned flight simulator rather than real aircraft piloted into low-level wind shear environment.

The research recommends that the Turkel and Frost model be mated to the NCAR CP-4 Doppler radar, to be situated at Stapleton Airport, Denver, during the Joint Airport Weather Studies (JAWS) project, Summer 1982. This system should be operated in real time, providing maps of flight deterioration parameters within 20 km of the airport, with an update rate no less than once each 5 minutes. Further testing of thresholding should be made utilizing performance data of research and operational aircraft operating in the JAWS Project environment. Steps should be taken to provide real-time products to the FAA, Denver, if so desired. In any event, a quantitative evaluation of the real-time effectiveness of the system should be performed.

A secondary conclusion drawn from this research regards the ability of standard training flight simulators to respond adequately to low-level wind shear. A strong indication was found of overdamped response at the long period mode phugoid frequency. In concert with this finding is the growing awareness that nature creates low-level wind shear such as the microburst at or close to scale lengths appropriate to the phugoid frequency. If adequate training simulators are not dealing with this scale of motion, steps should be taken to: (1) inform, and (2) correct the situation. Furthermore, a similar problem may exist on research and engineering simulators. Steps must be taken to identify and correct problems in this area as well.

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16. ABSTRACT

A study is made of manned flight simulator response to theoretical wind shear profiles in an effort to calibrate fixed-stick and pilot-in-the-loop numerical models of jet transport aircraft on approach to landing. Simulator flight tests were conducted at United Airlines, Denver, Colorado. Results of the study indicate that both fixed-stick and pilot-in-the-loop models overpredict the deleterious effects of aircraft approaches when compared to pilot performance in the manned simulator. Although the pilot-in-the-loop model does a better job than does the fixed-stick model, the study suggests that the pilot-in-the-loop model is suitable for use in meteorological predictions of adverse low-level wind shear along approach and departure courses to identify situations in which pilots may find difficulty. The model should not be used to predict the success or failure of a specific aircraft. Finally, the study suggests that the pilot model be used as part of a ground-based Doppler radar low-level wind shear detection and warning system.

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